Thermoacoustic Applications in Breast Cancer Detection, Explosive Detection and Communications

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Outline

- Introduction
  - Thermoacoustic Effect
  - Microwave-Induced Thermoacoustic Imaging
- Previous Work
  - Breast Cancer Detection
  - Experimental Validation of Modeling Method
  - Explosive Detection
  - Thermoacoustic Communication
- Conclusions

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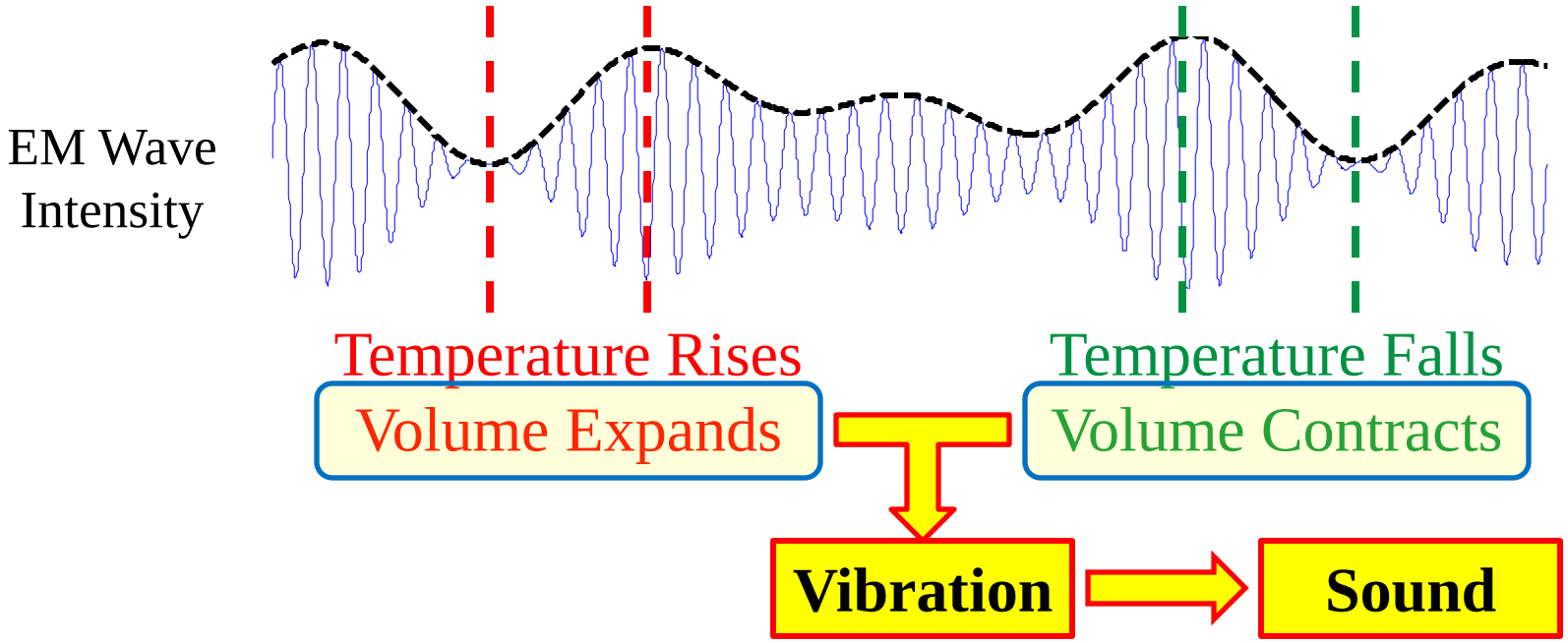
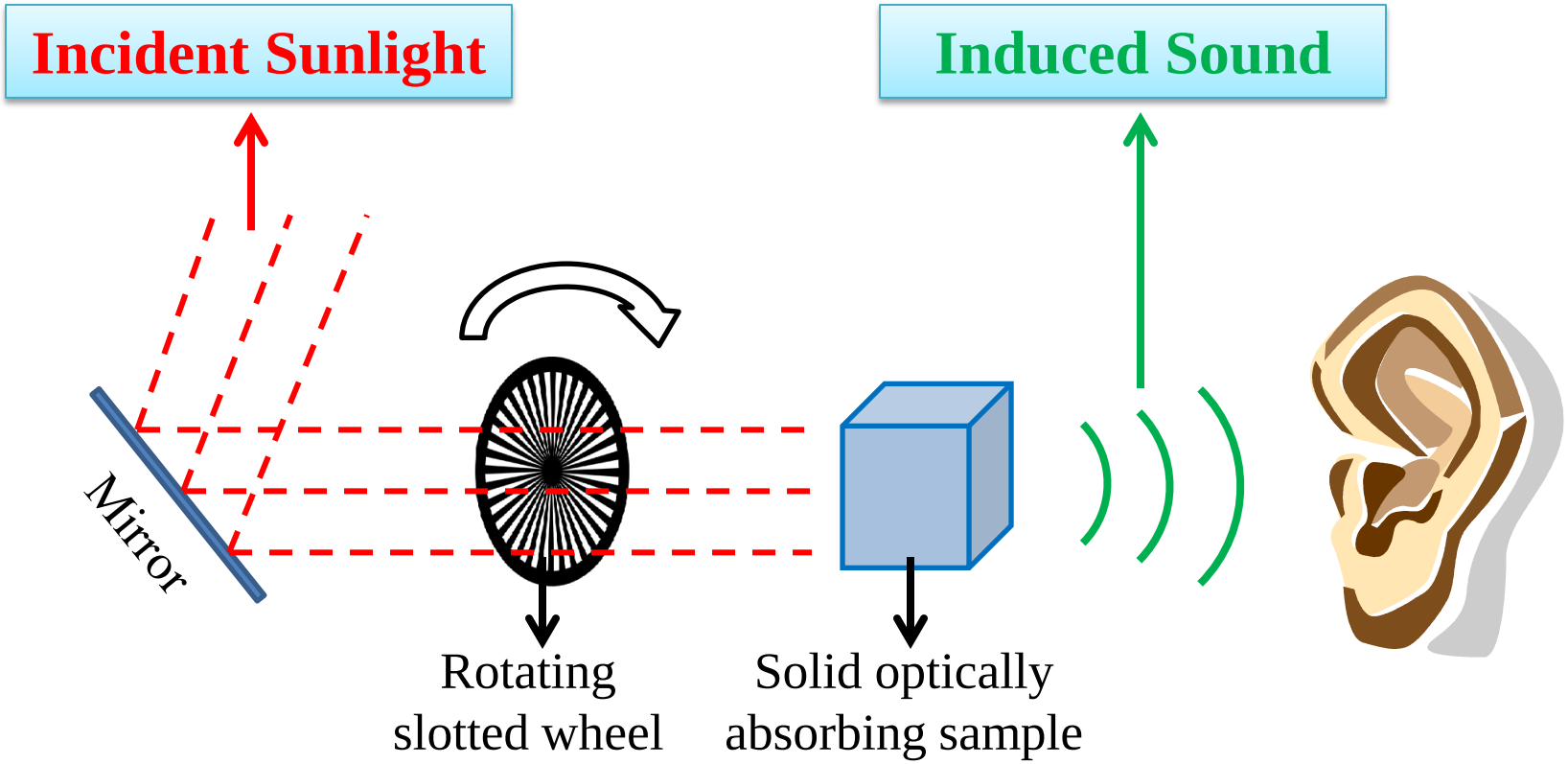
Thermoacoustic Effect

- Generation of sound by absorbed electromagnetic energy in sample
- Incident electromagnetic wave intensity must be modulated or usually in the form of a pulse
- Microwave, optical (photoacoustic/optoacoustic)



Discovery

- Discovered by Alexander G. Bell in 1880



A. G. Bell, *J. Franklin Inst.*, vol. 111, pp. 401-426, 1881.

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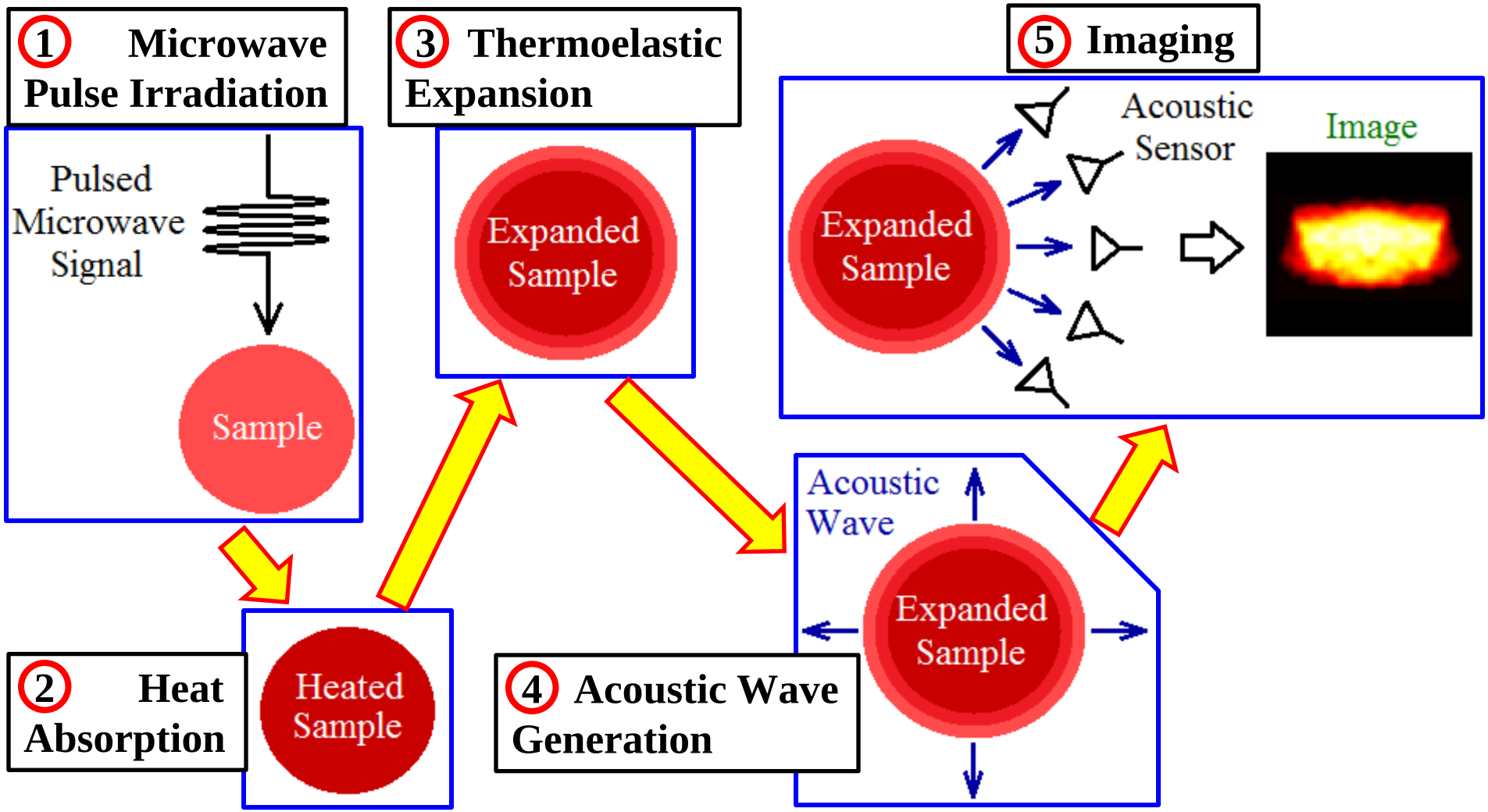
Microwave-Induced Thermoacoustic Imaging (TAI)



Kruger et al., *Radiology*, vol. 216, pp. 279-283, 2000.

G. Ku, and L. V. Wang, *Med. Phys.*, vol. 28, no. 1, pp. 4-10, Jan. 2000.

Advantages, Applications and Parameters

Advantages

- High contrast (microwave imaging)
- High resolution ~mm (ultrasound imaging)
- Easy imaging procedure (<10% acoustic heterogeneity)
- Noninvasive
- Low cost of implementation

Applications

- Breast cancer, brain cancer, prostate cancer
- Foreign body detection, renal calculi detection

General Parameters

- Pulse width: ns − μs
- Microwave frequency: below 10 GHz; peak power: kW
- Acoustic signal frequency: kHz − MHz

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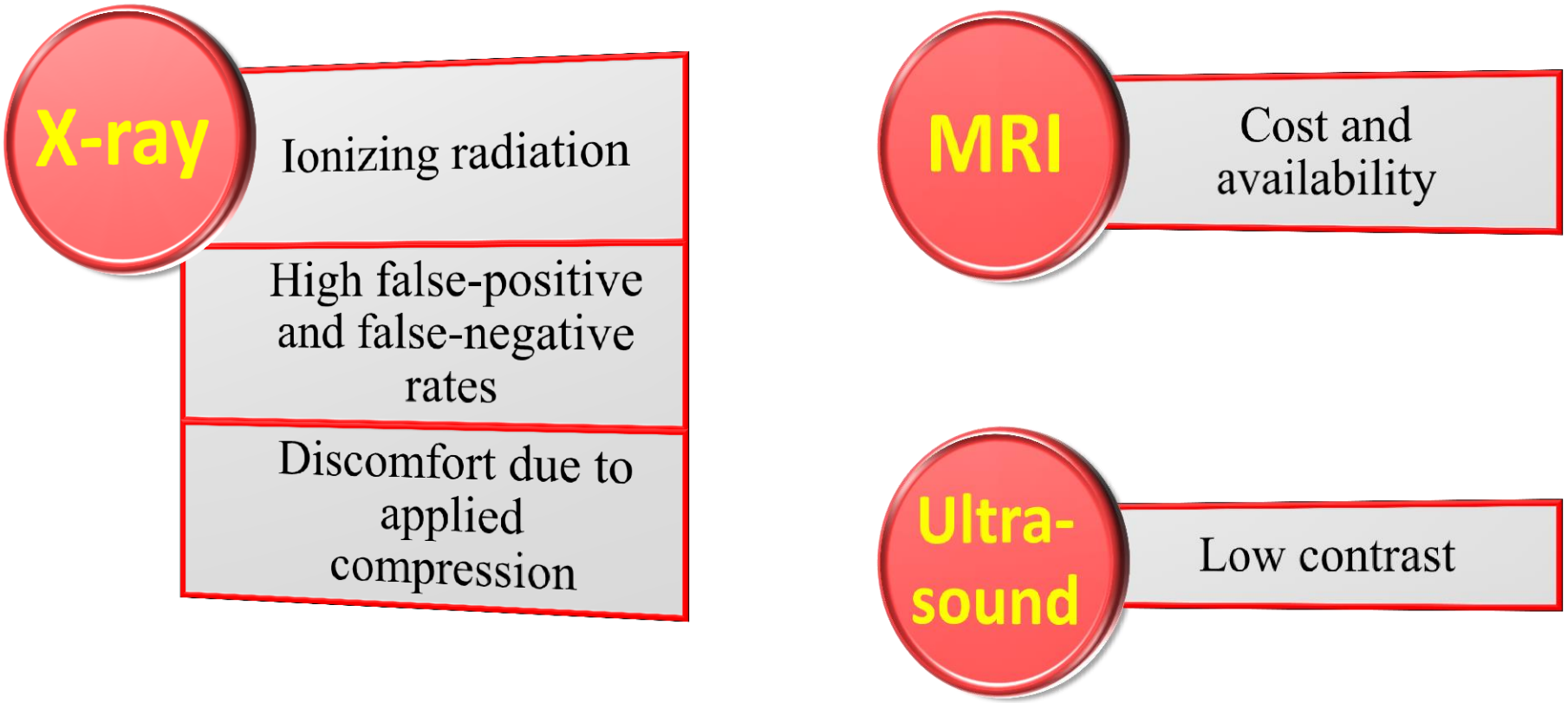
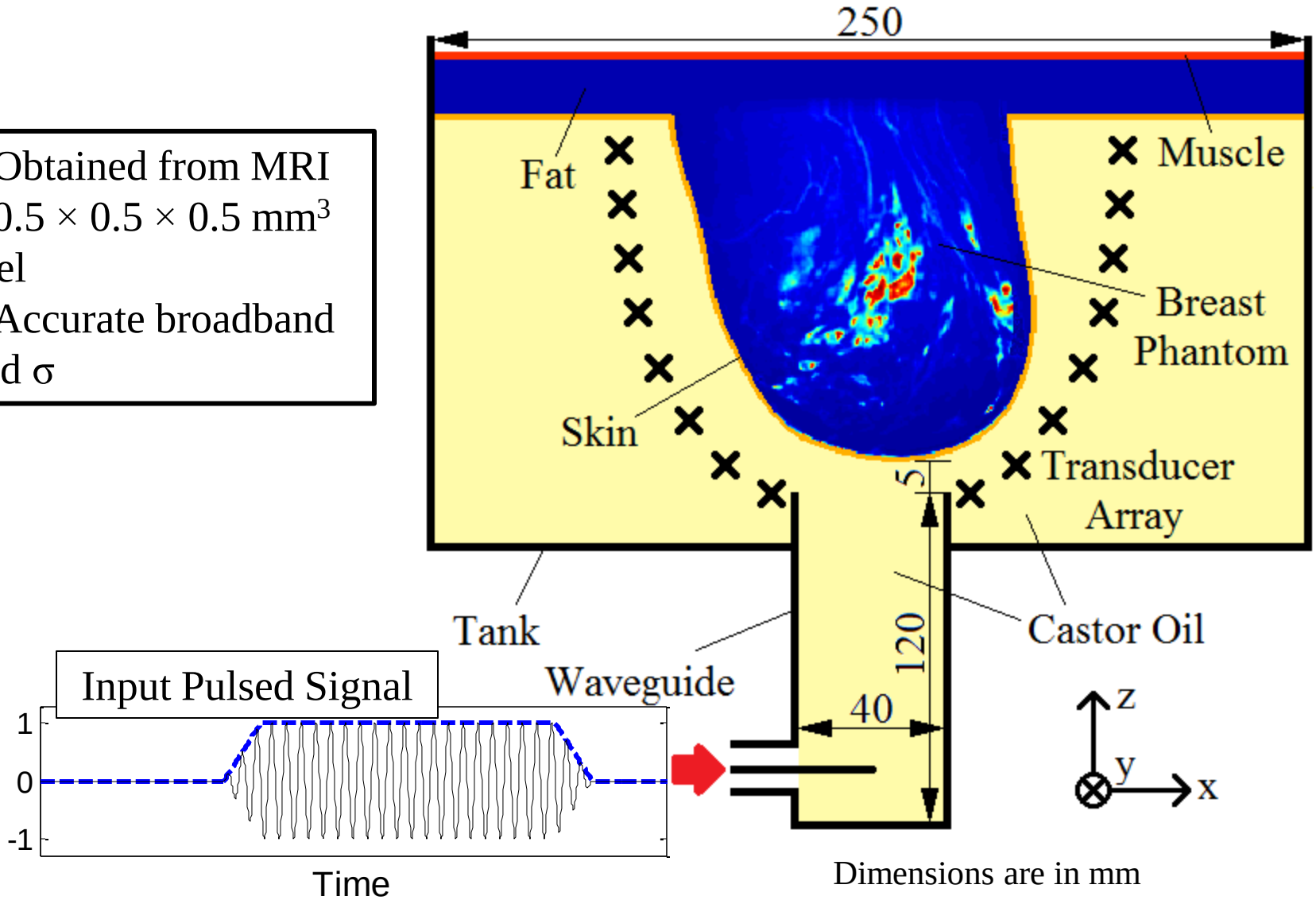
Motivation


X-ray
Ionizing radiation
High false-positive and false-negative rates
Discomfort due to applied compression
MRI
Cost and availability
Ultra-sound
Low contrast

Numerical Modeling

- Obtained from MRI
- $0.5 \times 0.5 \times 0.5$ mm^3 voxel
- Accurate broadband ε and σ



X. Wang, *et al*, *IEEE Trans. Biomed. Eng.*, vol. 59, no. 10, pp. 2782-2791, Oct. 2012.

Simulation Method

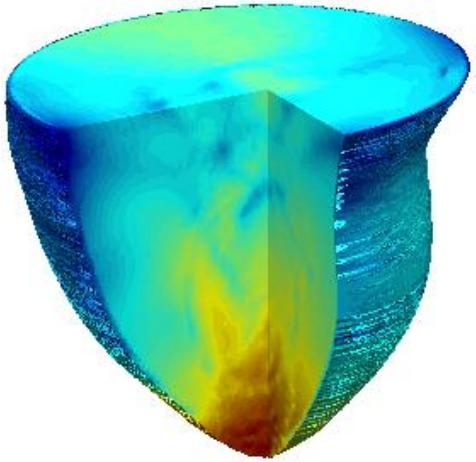
Stage I: EM Modeling

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$

$$\nabla \times \vec{H} = j\omega\varepsilon\vec{E} + \vec{J}$$

$$\mathrm{SAR}(\vec{r},t) = \frac{\sigma(\vec{r})\left|\vec{E}(\vec{r})\right|^2}{\rho(\vec{r})} I(\vec{r},t)$$

$\left|\vec{E}(\vec{r})\right|$



Solved by EM FDTD Software

Microwave Energy Absorption

Acoustic Pressure

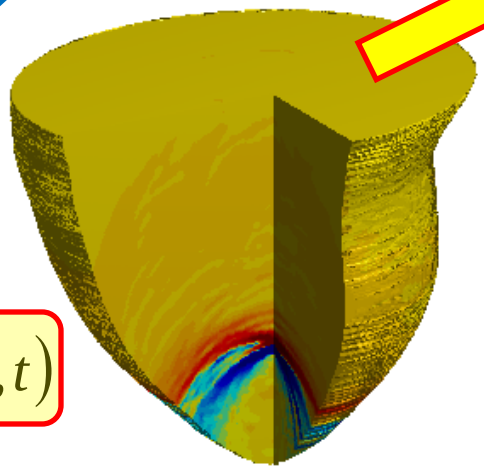
Imaging

Stage II: Acoustic Modeling

$$\rho\frac{\partial}{\partial t}\vec{u}(\vec{r},t) = -\nabla p(\vec{r},t)$$

$$\nabla\cdot\vec{u}(\vec{r},t) = -\frac{1}{\rho c^2}\frac{\partial}{\partial t}p(\vec{r},t) + \frac{\beta}{C_p}\mathrm{SAR}(\vec{r},t)$$

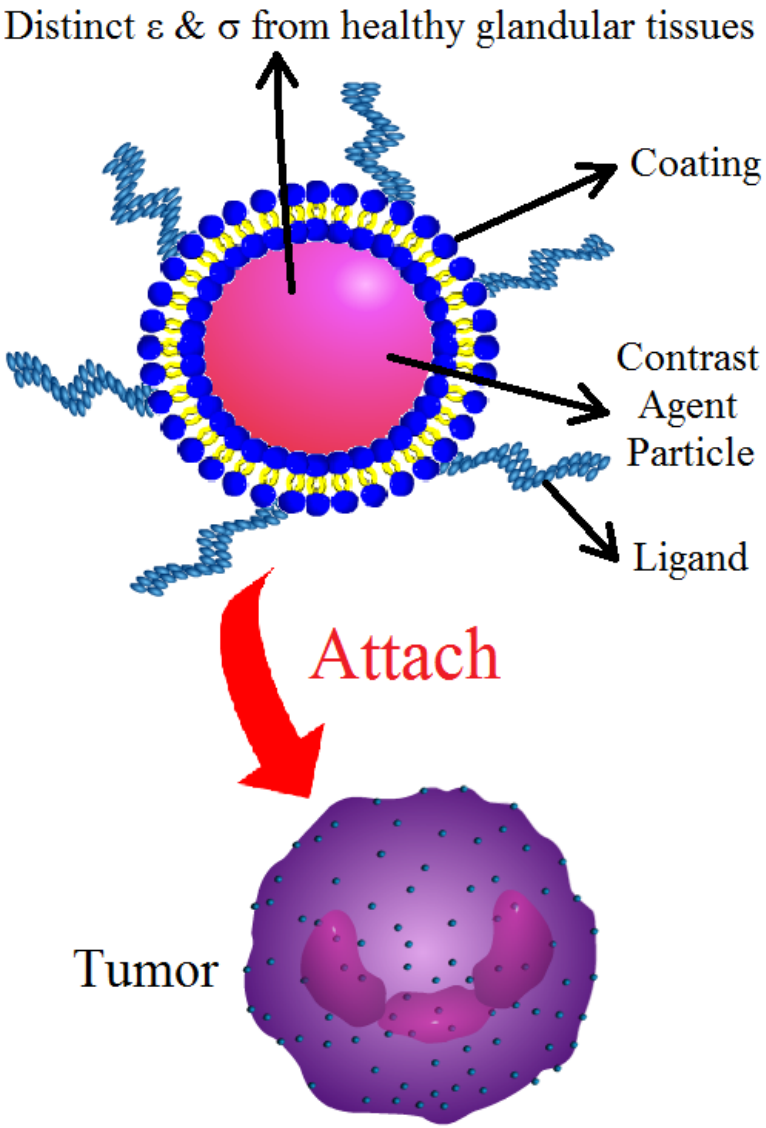
$p(\vec{r},t)$



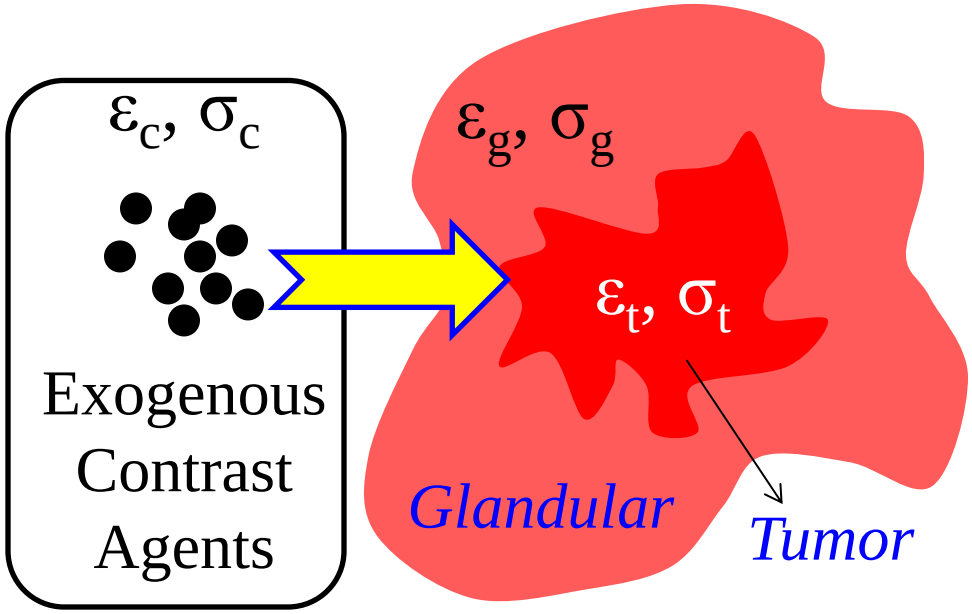
Solved by acoustic FDTD or PSTD code

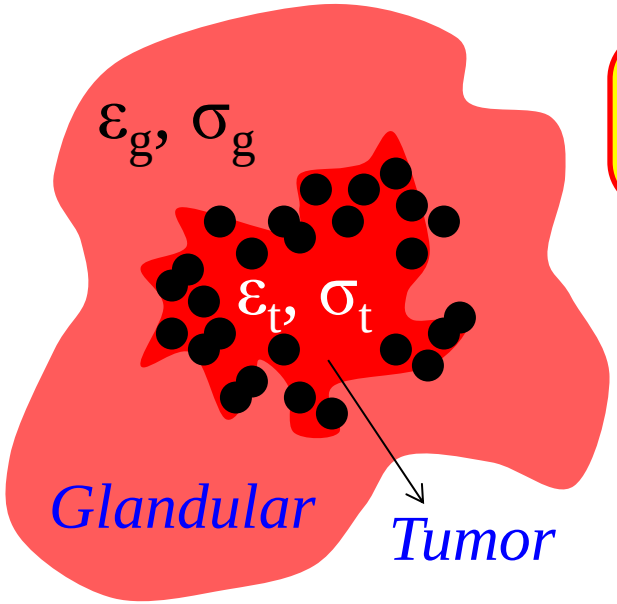
Q. H. Liu, *IEEE Trans. Ultrason., Ferroelect.*, Freq. Control., vol. 45, no. 4, pp. 1044–1055, Jul. 1998.

Contrast-Enhanced TAI (CETAI)



M. Lazebnik, *et al*, *Phys. Med. Biol.*, vol. 52, pp. 6093–6115, 2007.



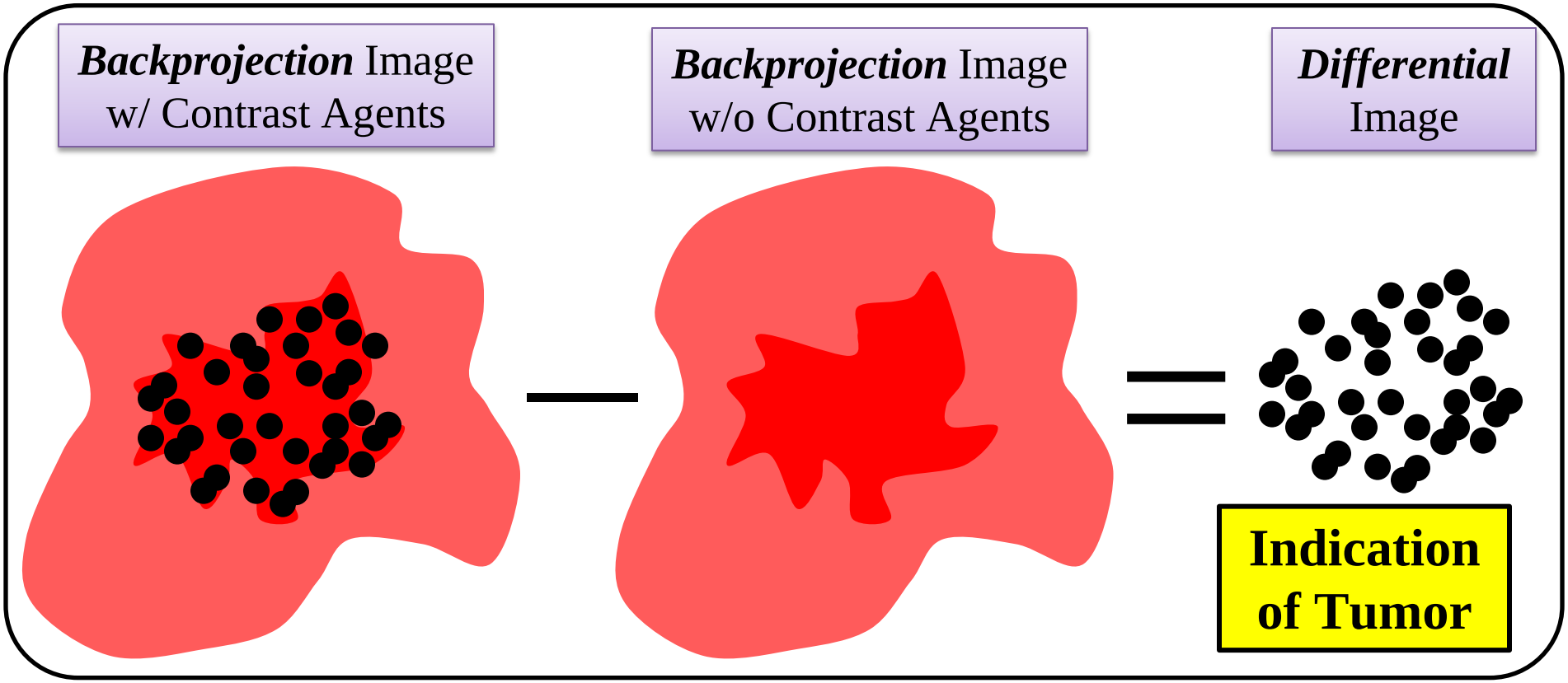


High Contrast
5 : 1

Enhance Imaging Quality

Imaging Method

Backprojection Imaging & Differential Imaging



Contrast Agents for TAI

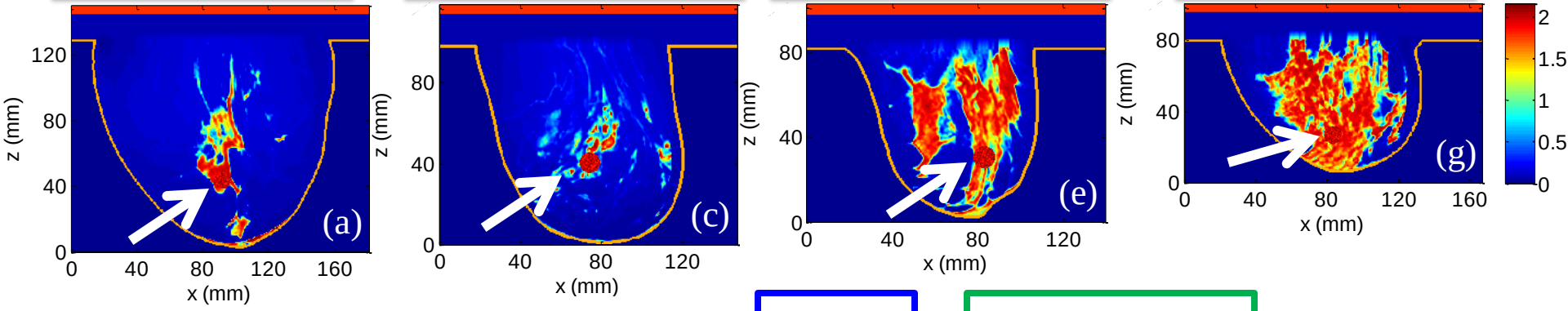
- Microbubbles (*decrease tumor* ε, σ *and TA signal*)
- Magnetic nanoparticles like Fe_3O_4 (*increase TA signal*)
- Single-walled carbon nanotubes (SWCNTs) (*increase tumor* ε, σ *and TA signal*)
- Effects of SWCNTs on tumor-mimicking materials have been well-quantitatively investigated

CETAI with Realistic Numerical Breast Phantoms

Conductivity Profiles

X. Wang, *et al*, submitted to *IEEE Trans. Microwave Theory and Techniques.*

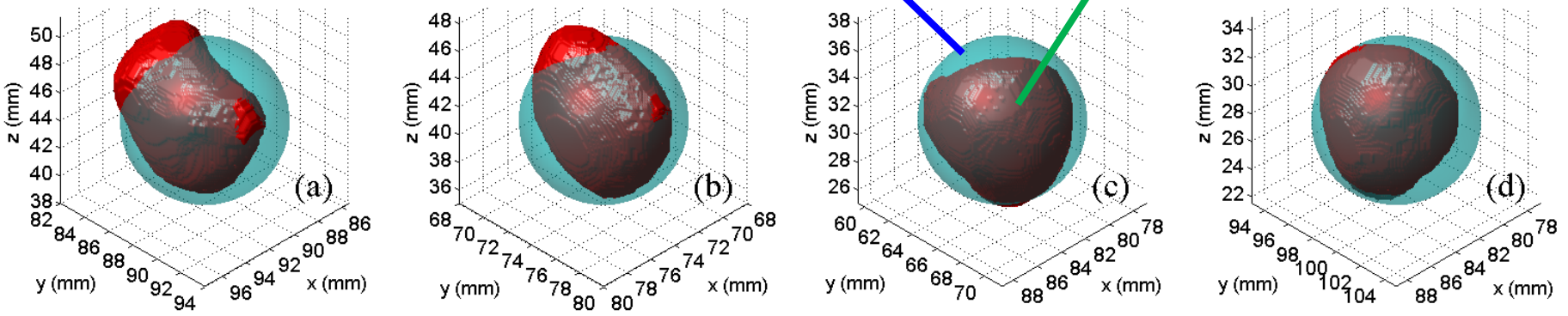
Class 1 (<25%) | Class 2 (25~50%) | Class 3 (50~75%) | Class 4 (>75%)



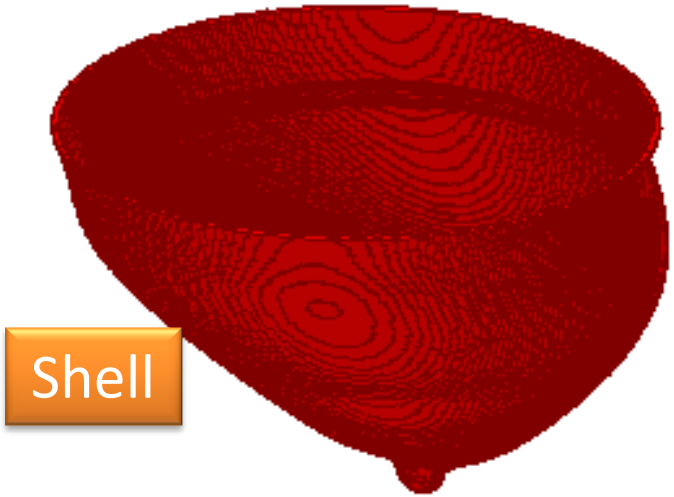
3D Differential Images

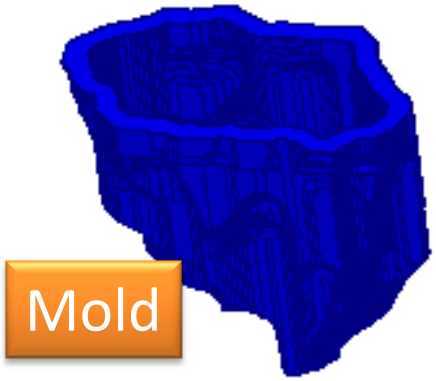
Actual tumor

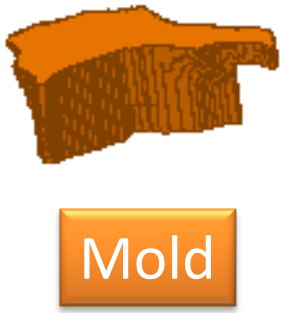
Reconstructed 3-D tumor

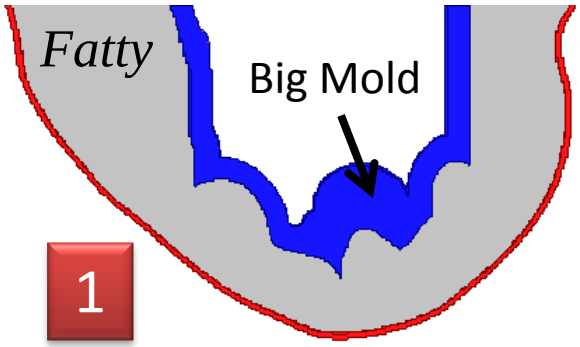


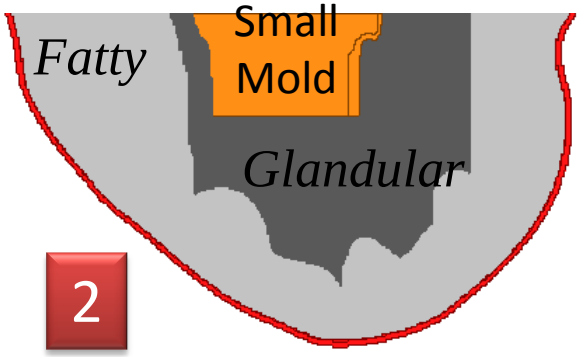
Fabrication of Breast Phantom

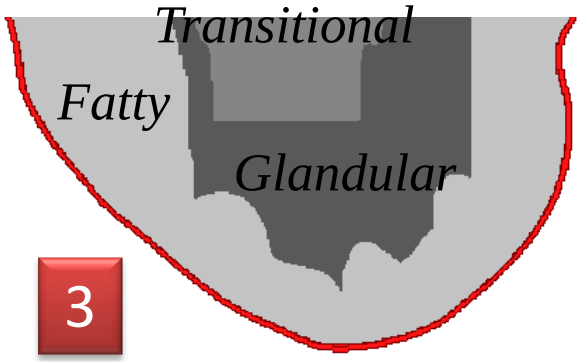








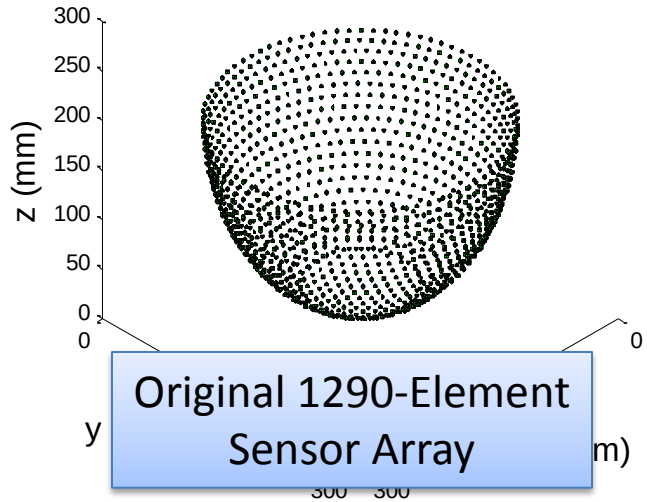




Combine Compressive Sensing

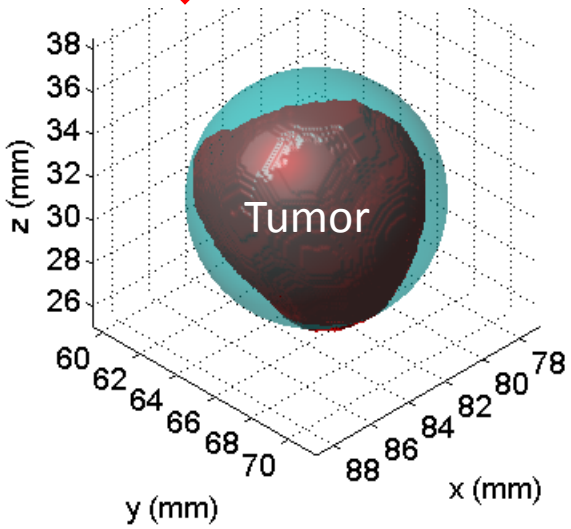
- Compressive sensing (CS) takes advantage of the signal's sparseness to significantly reduce the needed measurements that breaks the Nyquist-Shannon sampling theorem
- Optimization methods are used to reconstruct image
- CS Can help to greatly expedite breast cancer screening and other TAI applications

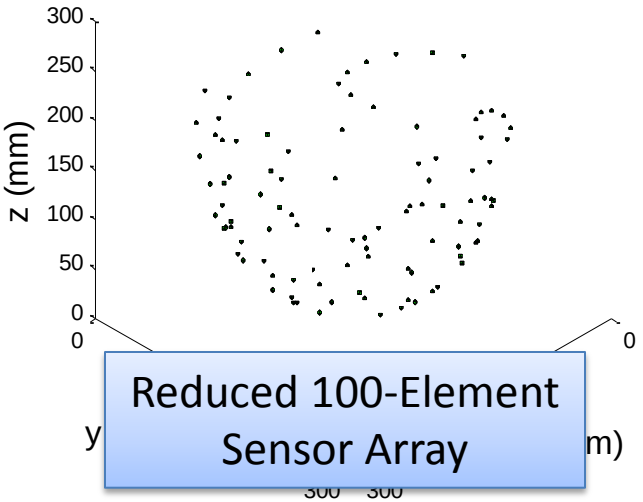
Simulation Results (3D)



Original 1290-Element Sensor Array

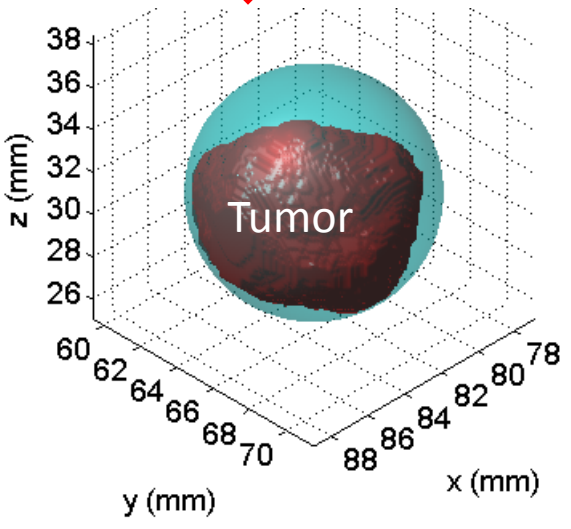
Backprojection

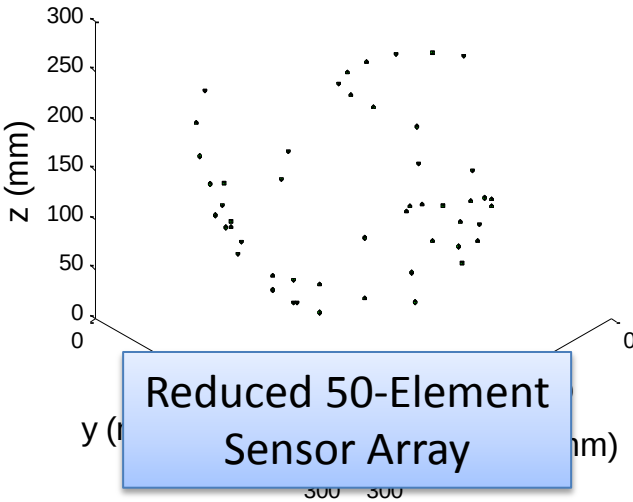




Reduced 100-Element Sensor Array

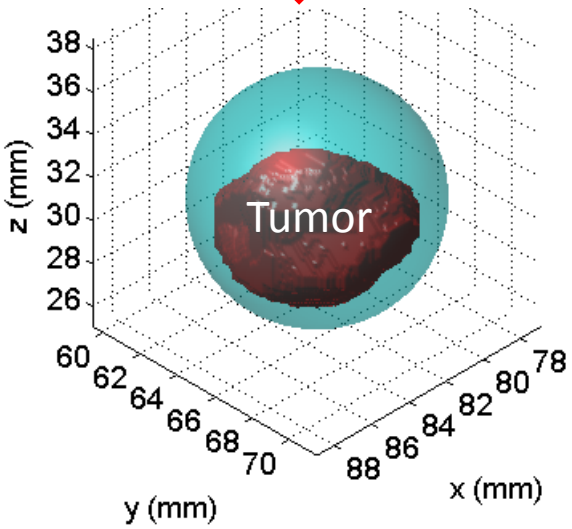
CS





Reduced 50-Element Sensor Array

CS



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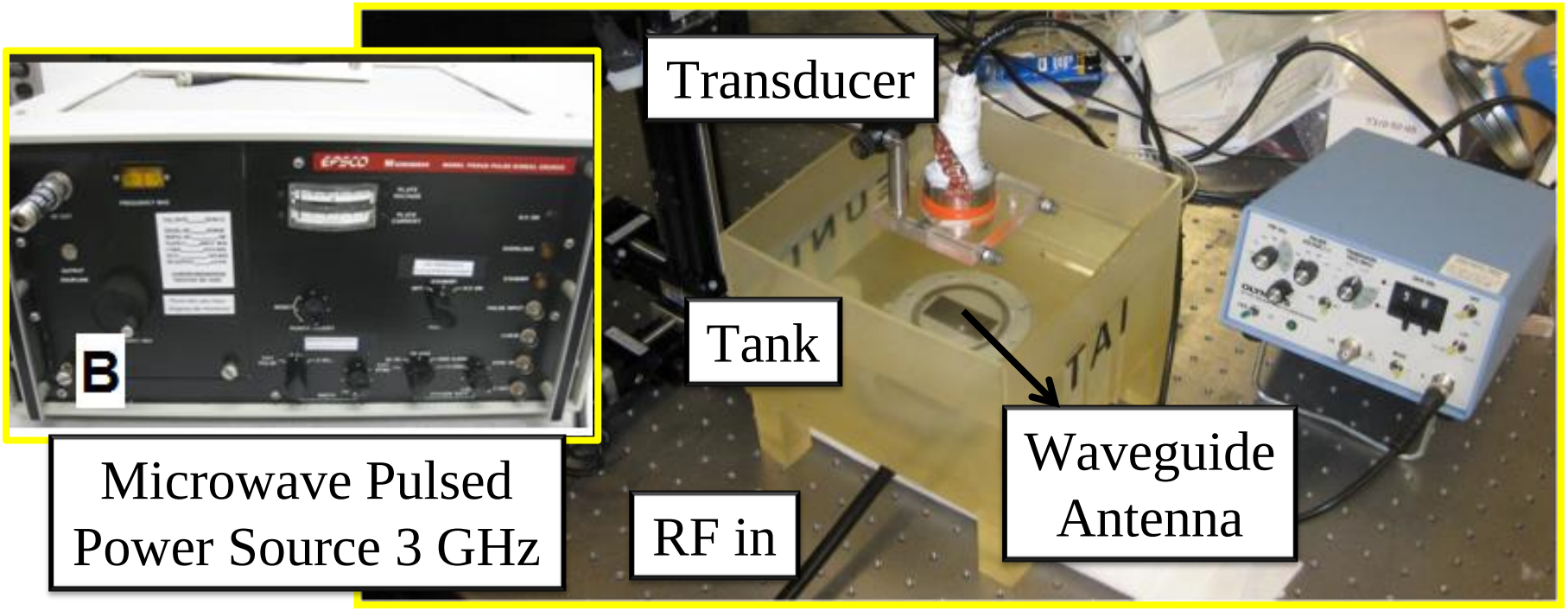
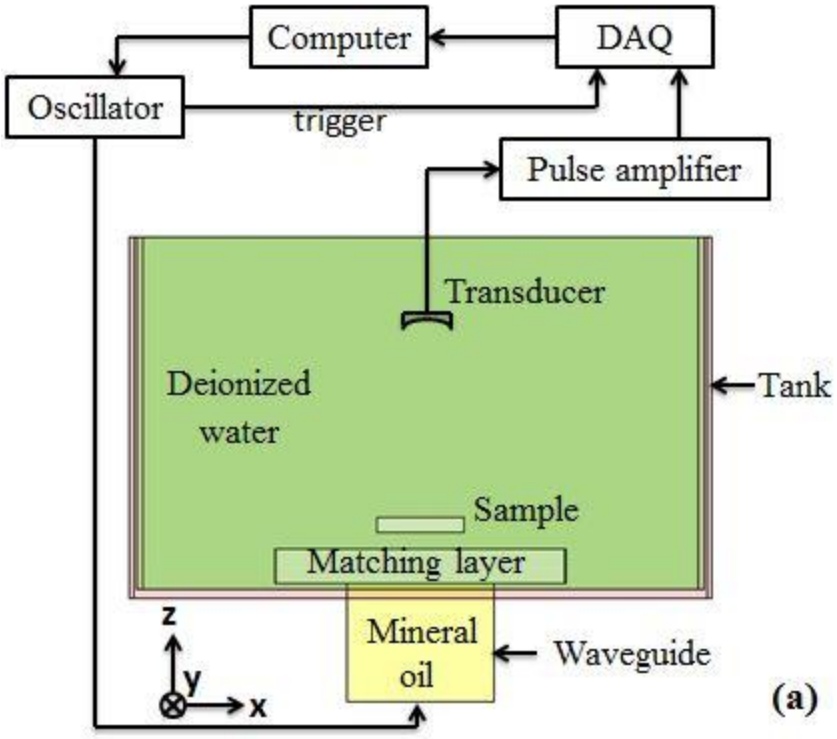
Experimental System

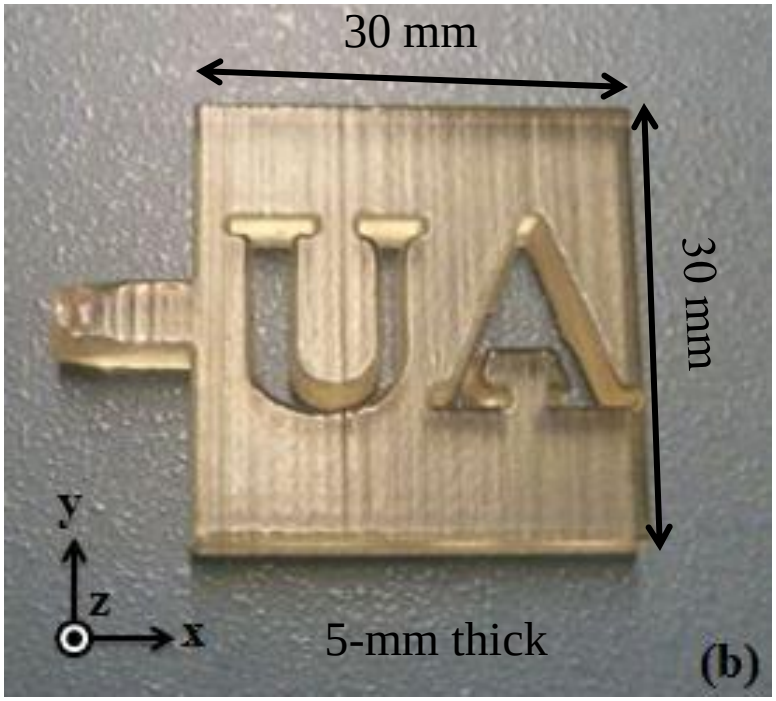
- Microwave Source
  - 1.2 − 1.4 GHz, 25 kW peak power
  - 2.5 − 3.1 GHz, 5 kW peak power
  - 8 − 12 GHz, 1 kW peak power
- ≤ 100 ns Pulse Width (High Resolution)



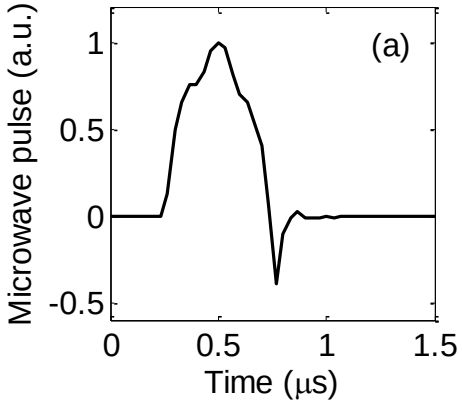
D. Bauer, X. Wang, *et al*, *Appl. Phys. Lett.* vol. 101, no. 3, pp. 033705:1-4, Jul.. 2012.

Test a Printed Featured Slab





Input Pulse in Experiment



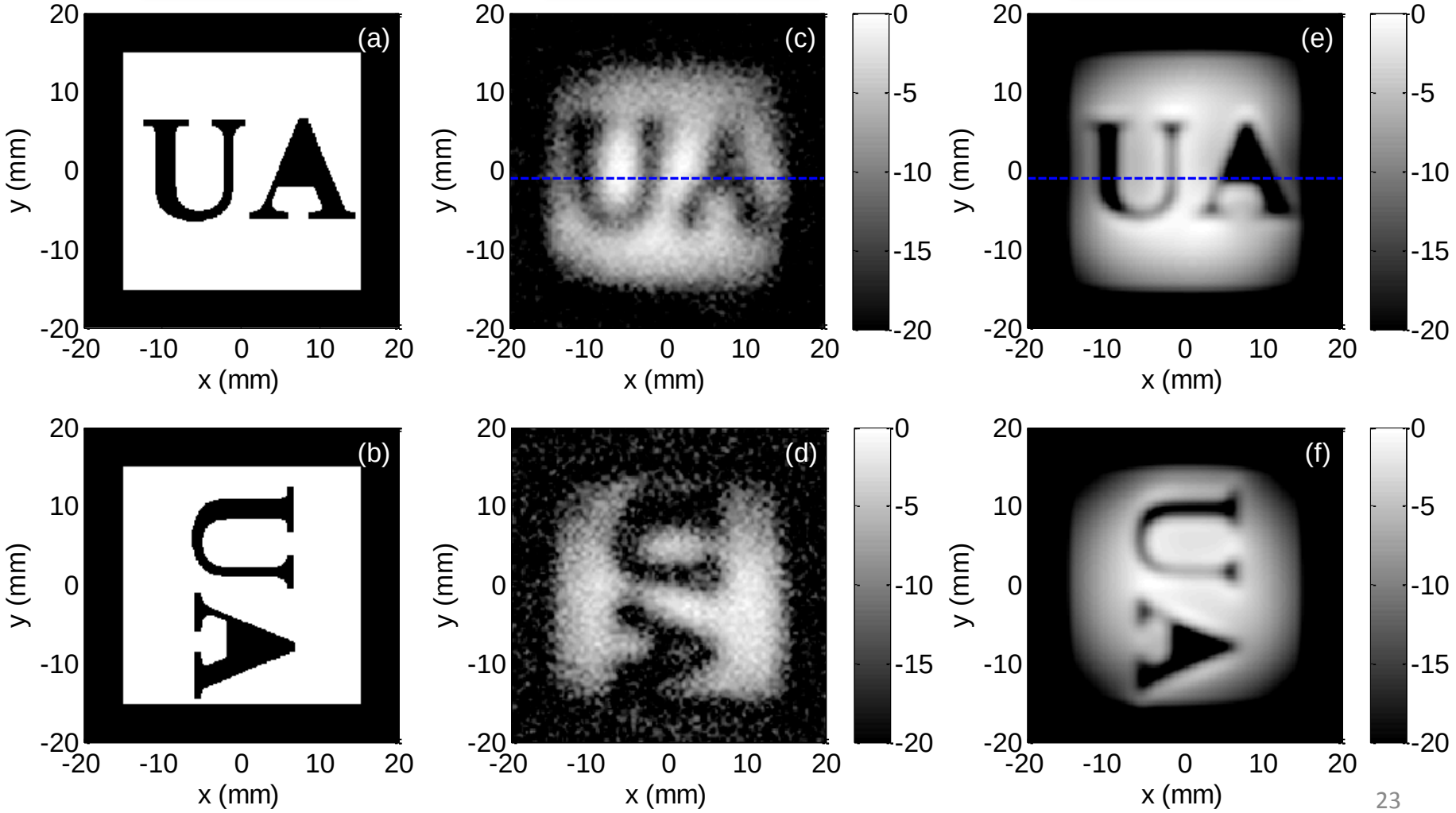
- Printed with polymer using 3-D printing technology
- The hollow "UA" has a smallest slot of 1.1 mm
- Polymer's dielectric and acoustic properties are accurately measured and used in simulations

Experimental and Simulation Results

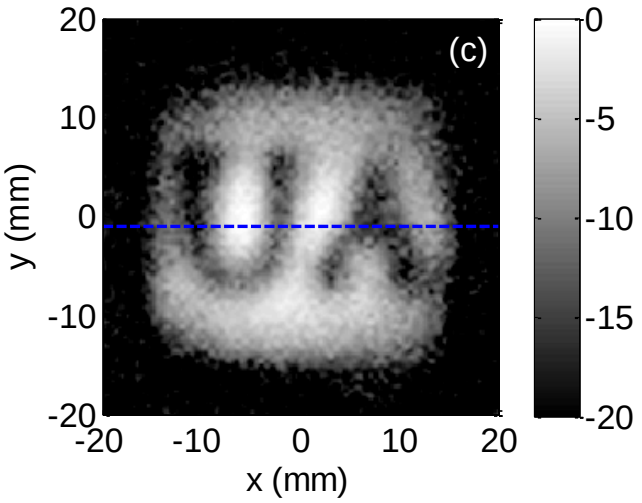
Schematic Showing

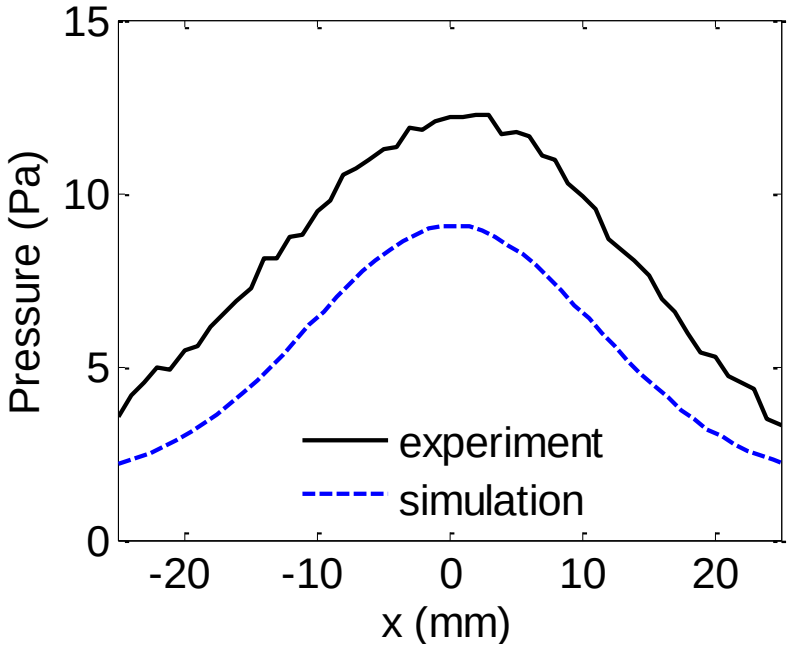
Experimental Images

Simulation Images



Quantitative Comparison





T. Qin, X. Wang, *et al*, submitted to *Appl. Phys. Lett.*

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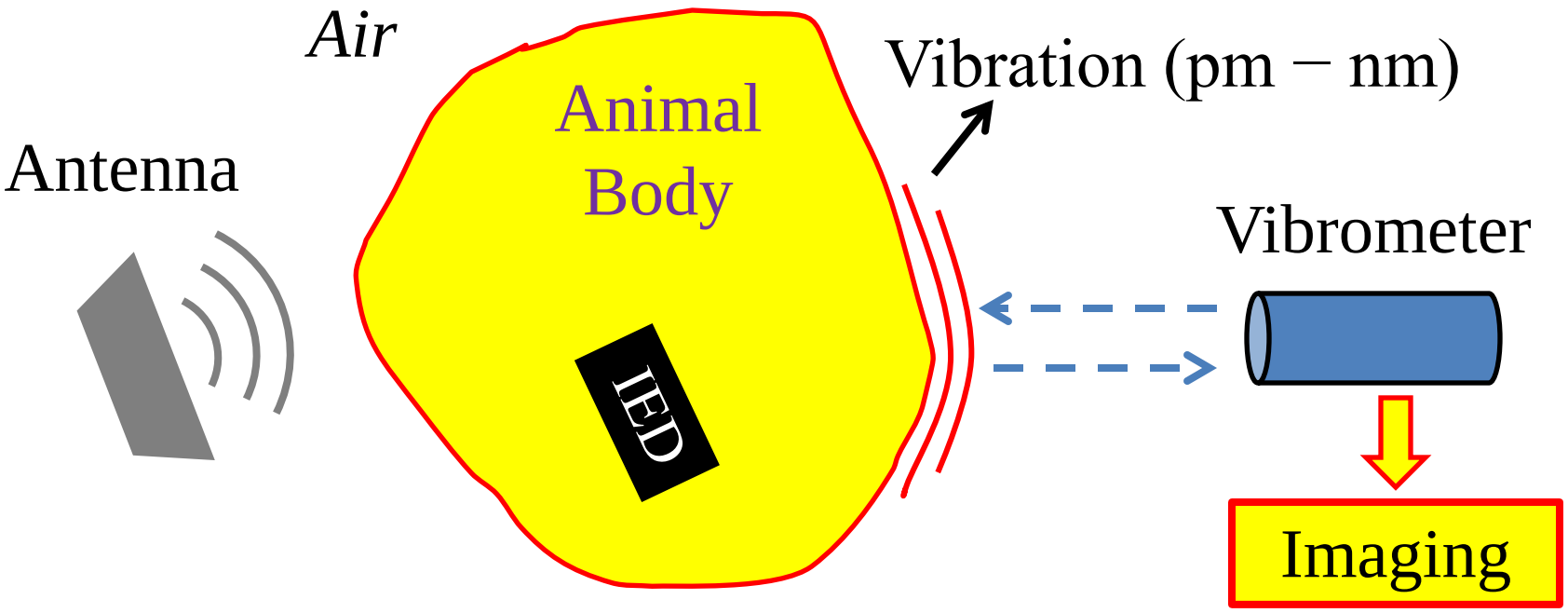
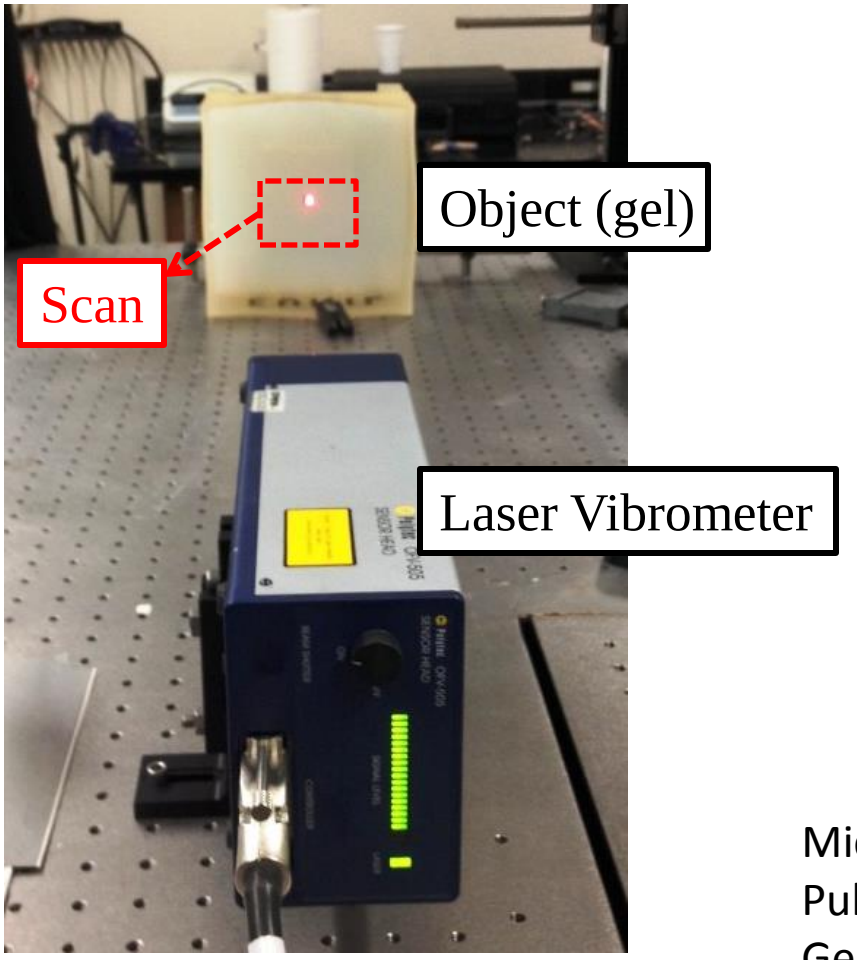
Motivation

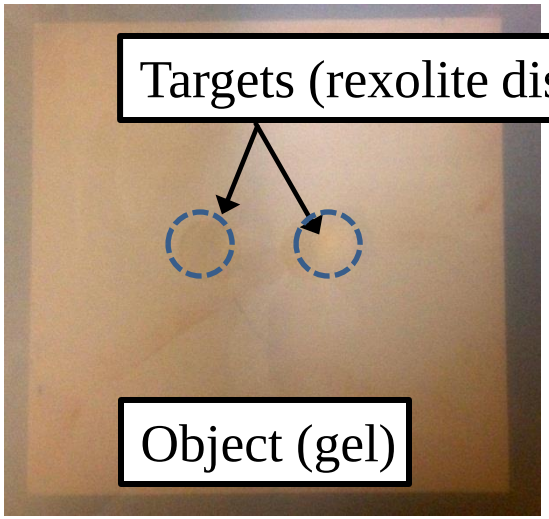
- Improvised explosive devices (IED) embedded in high-water content, like dead animal body, have been a major threat to personnel
- X-ray is most widely used, but ionizing radiation poses a potential hazard
- Non-contact detection is highly desired
- Explosive has much lower dielectric loss than animal body. So this contrast can be explored by TAI. Different from breast cancer detection, explosive here is a cold target

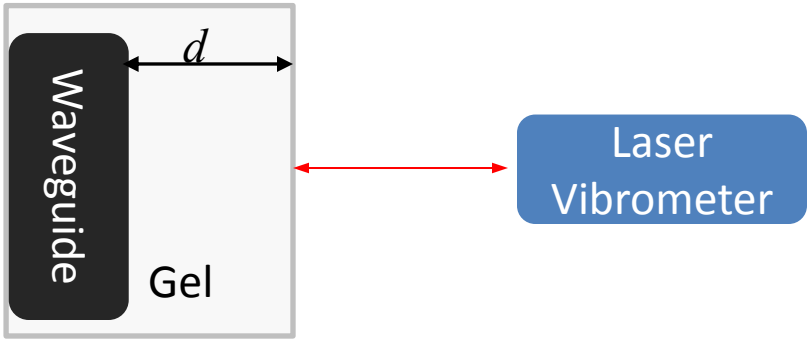
Non-Contact Detection by TAI



Experimental Setup



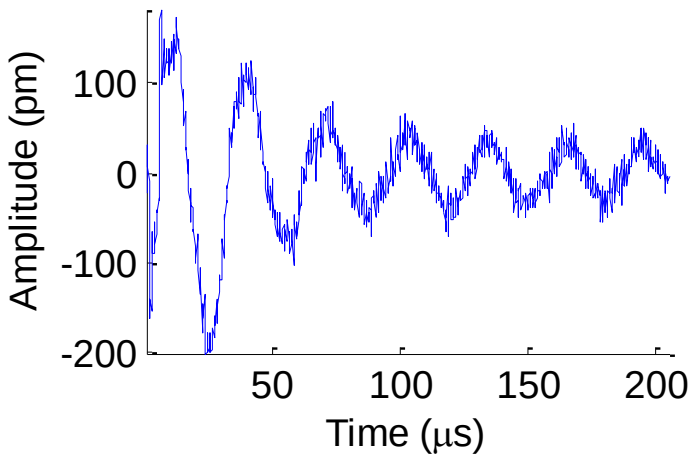




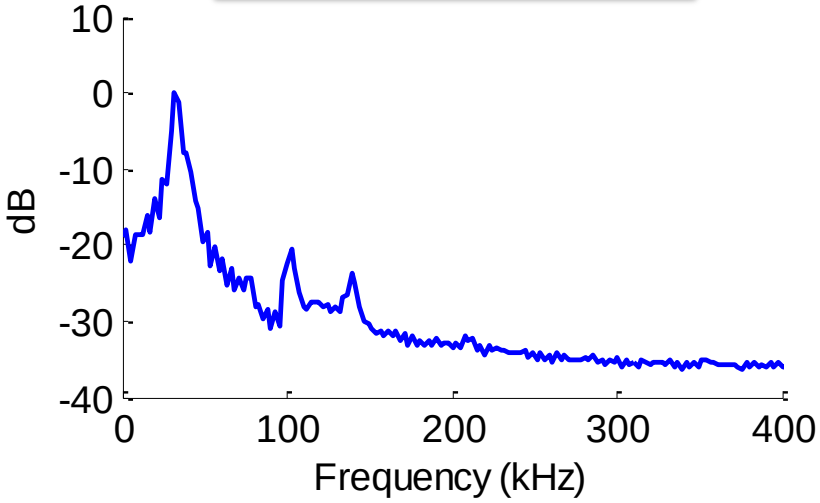
Microwave:	4kW @ 3GHz
Pulse width:	4.0 μs
Gel thickness (d):	20 mm

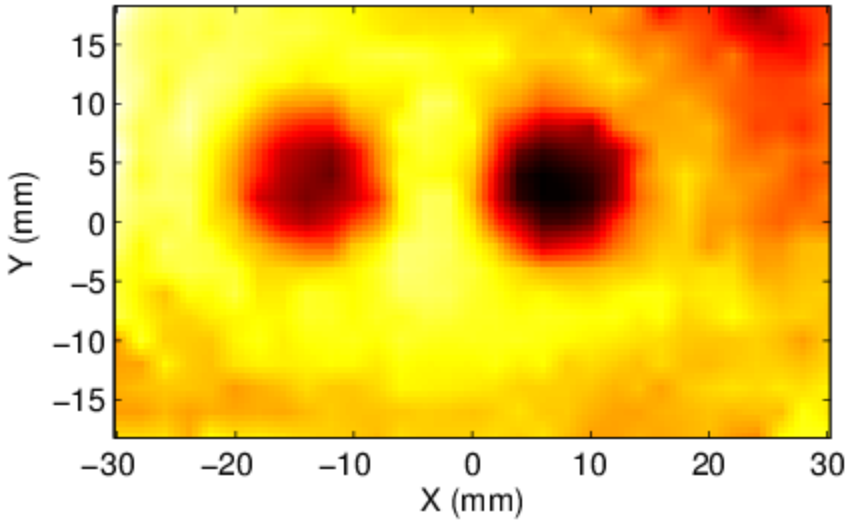
Experimental Results

Measured Time-Domain Displacement



Frequency-Domain Displacement





First Non-Contact Image of TAI

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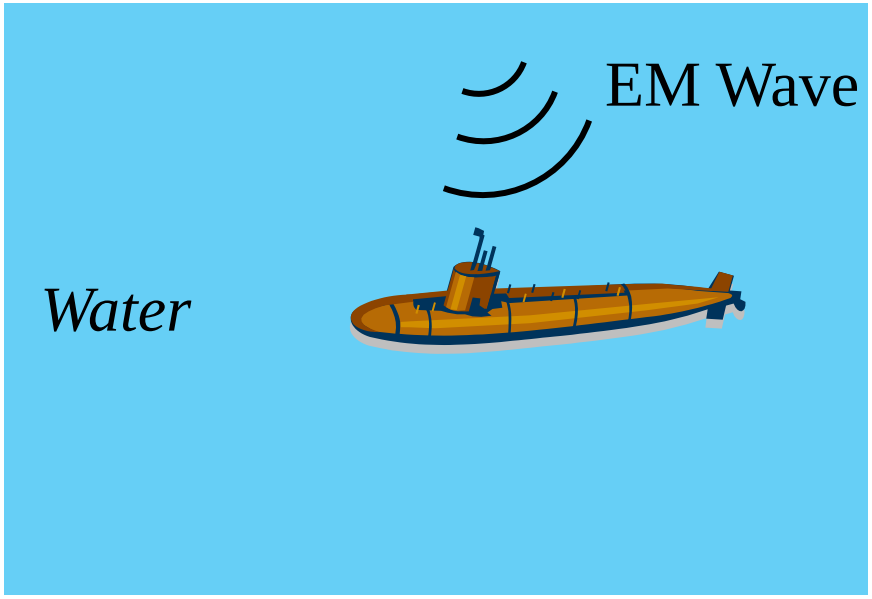
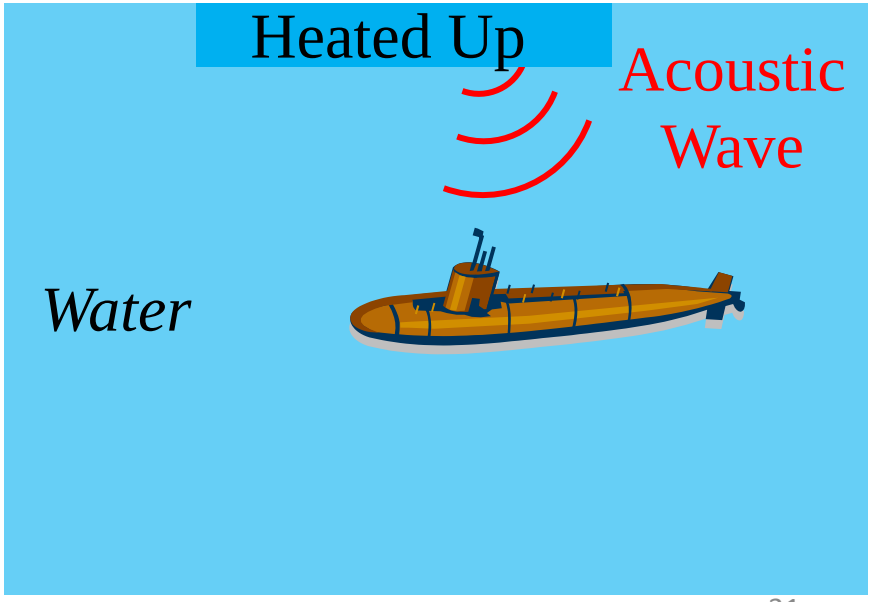
Motivation

Conventional Method

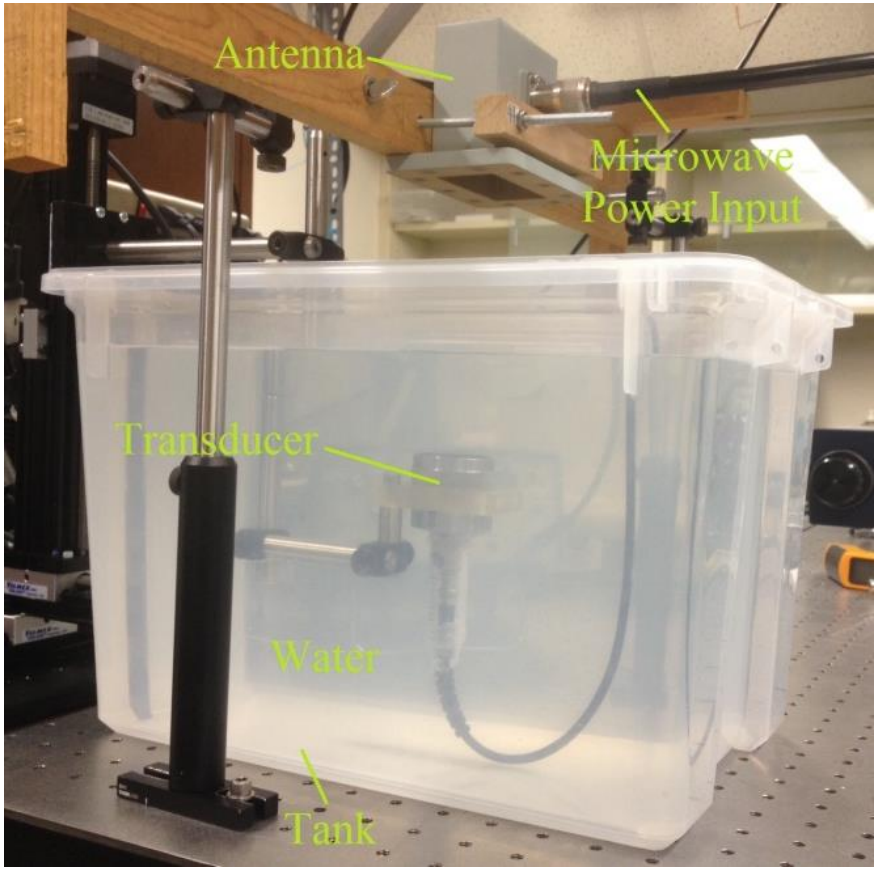


Thermoacoustic Communication

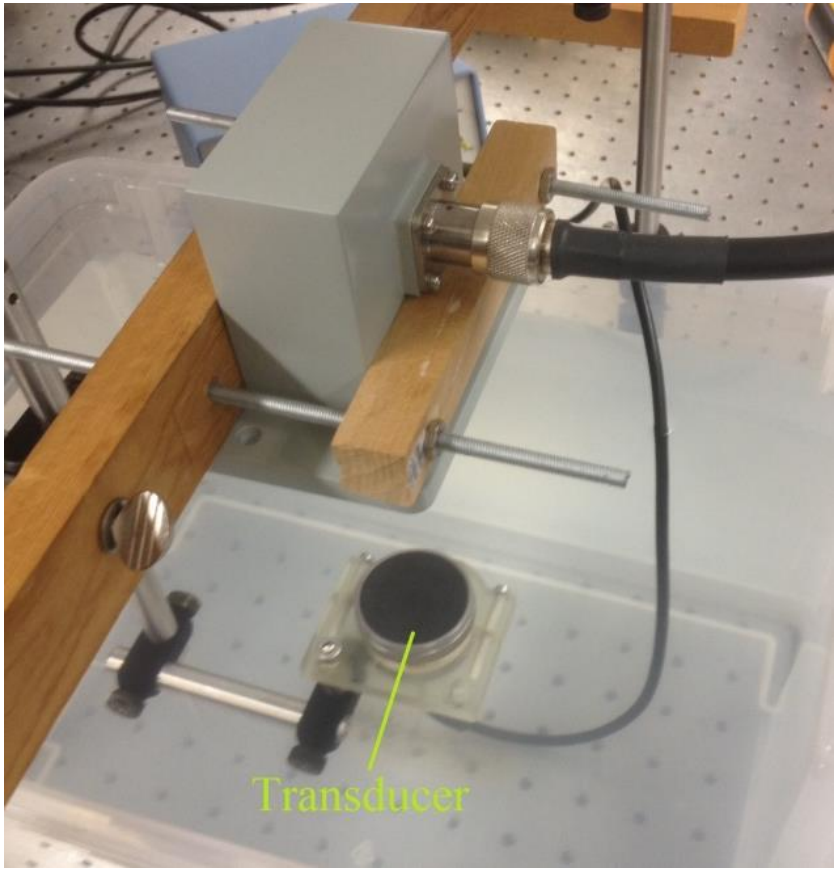


Proof-of-Concept Experiment

Side View



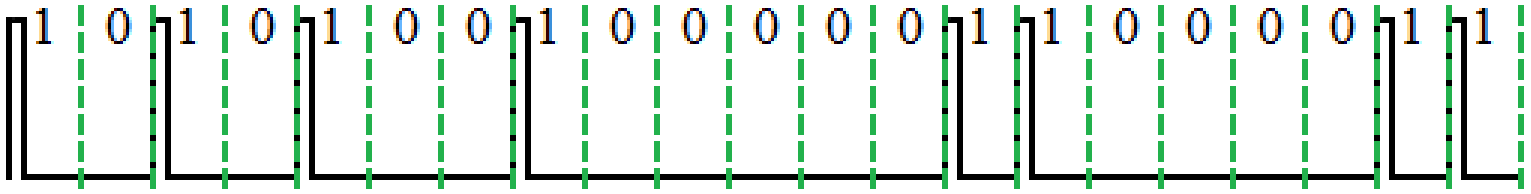
Top View



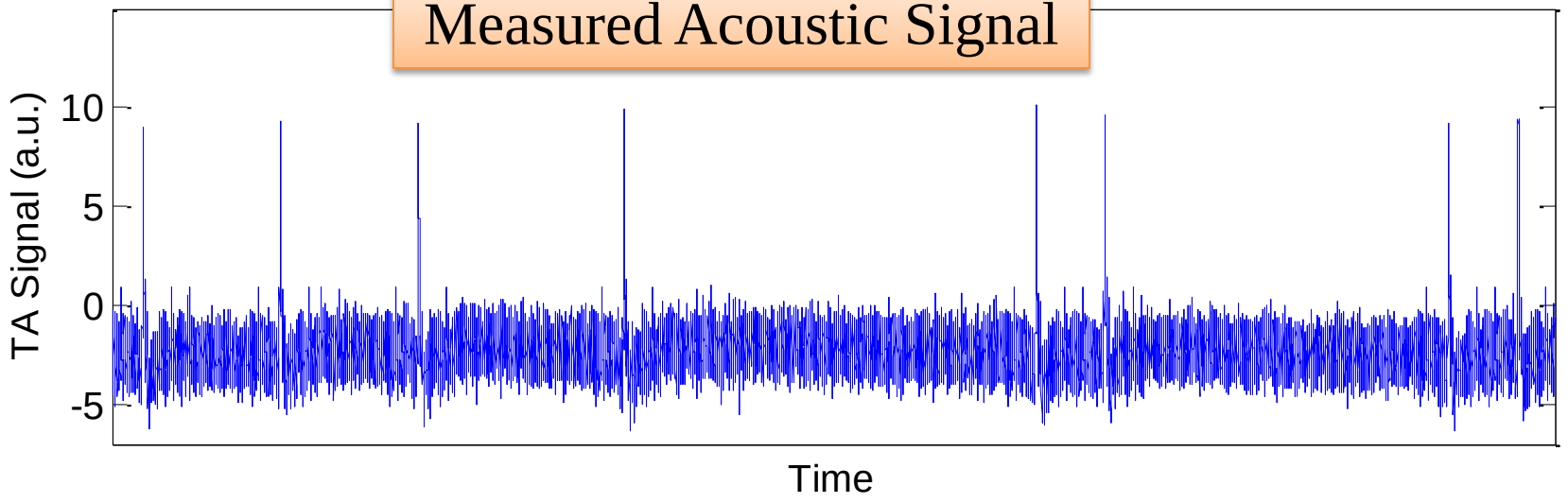
Experimental Results

Letter	T	A	C
ASCII Code	1010100	1000001	1000011

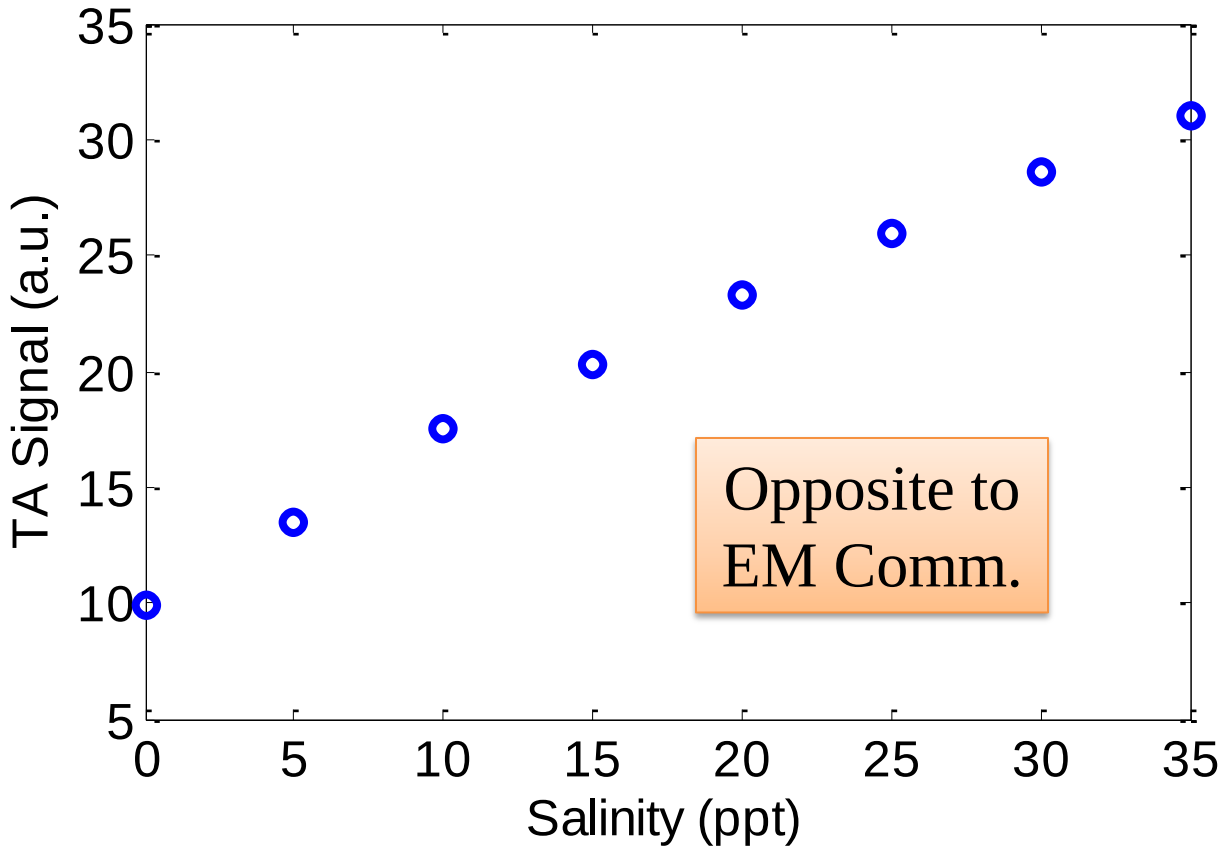
Data Sequence



Measured Acoustic Signal



Dependence on Water Salinity



Limitation

- Generated acoustic signal level is low
- Solutions: Very high power, Super high gain antenna

Outline

- Introduction
  - Thermoacoustic Effect
  - Microwave-Induced Thermoacoustic Imaging
- Previous Work
  - Breast Cancer Detection
  - Experimental Validation of Modeling Method
  - Explosive Detection
  - Thermoacoustic Communication
- Conclusions

Conclusions

- Thermoacoustic effect has promising applications in many areas
- Build numerical TAI models to simulate realistic breast phantoms and show good performance in different phantoms using contrast agents
- Modeling method has been verified by experiments
- Combining CS to TAI is very promising to expedite breast cancer detection
- Non-contact TAI is promising for explosive detection
- Thermoacoustic communication has been experimentally demonstrated, but has limitations to be overcome

Thank you!